# Multi-frequency Tomography Radar Observations of Snow Stratigraphy at Fraser during SnowEx

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***Abstract*— SnowEx is a multi-year airborne snow campaign led by NASA. The purpose of SnowEx is to figure out how much water is stored in Earth's terrestrial snow-covered regions. As part of the 2017 NASA SnowEx campaign, we deployed a portable triple-frequency (9.6GHz, 13.5GHz and 17.2GHz) and fully polarimetric frequency-modulated continuous-wave (FMCW) radar at Fraser, Colorado. The radar was installed on a 60cmx60cm frame to enable a full reconstruction of the three-dimensional variability per each radar channel. The tomography technique uses the radar echo from the multiple viewing positions and provides a unique access to the vertical structure of the snow layer. With current setup, the range resolution is 30cm. In this paper, we will review the radar design and signal-processing algorithm – time domain back projection. The generated vertical images show the snow stratigraphy, which is consistent with ground snow pit measurement. The continuous operation demonstrates diurnal thawing and refreezing process. The snow density is retrieved by comparing to the snow free image.**

***Keywords—component, formatting, style, styling, insert*** *(key words)*

## I. Introduction

The understanding of the seasonal snowpacks is critical for effective water resource management, weather/climate prediction and natural hazard forecasts [1]. The current Snow Water Equivalence (SWE) products derived from passive radiometer and data assimilation scheme cannot fully characterize in space and time consistently to meet the required accuracy. In the past few years, a number of mission concepts using X- and Ku-band SAR technology have been proposed for understanding the snow accumulation pattern globally [2]. All those concepts rely on the finer resolution of the SAR techniques to separate other environmental effects such as mixed vegetation cover or rough terrain in a single pixel and attempt to relate the backscattering to the Snow Water Equivalence (SWE). However, the terrestrial snow has the evolving vertical profiles along with the microstructure that complexly interacts with microwaves giving a variety of frequency, polarimetric and angular dependencies in scattering. A snowpack, that goes through several small storms and temperature variation, with the stratigraphy in layers of new snow, rounded grains and depth hoar can generate very different radar signals with the same amount of snow falling in from one big storm [3]. In return, it will cause large ambiguity in the retrieval algorithm. Traditionally, a snow stratigraphy is characterized through a snow pit study. It only represents a snapshot view of the snow vertical properties and cannot capture the continually evolving snow process. This type of study is also destructive and time-consuming. Recent studies show that by using multi-baseline SAR configuration, the tomographic processing can provide the vertical image of the snowpack and monitor temporal variability [4-6]. In the study, Preliminary tomographic processing of ground based SAR data of snowpack at X- and two Ku- band has revealed the presence of multiple layers within the snowpack and clear melting/refrozen cycle, which is consistent with the in-situ measurement.

## II. SRT Radar Design & Calibration

In the past two years, we have developed a homodyne frequency modulated continuous wave radar (FMCW), operation at three earth exploration satellite bands within the X-band and Ku-band spectrums (centered at 9.6 GHz, 13.5 GHz, and 17.2 GHz) at Jet Propulsion Laboratory. The transceiver is mounted to a dual-axis planar scanner (60cm in each direction), which translates the antenna beams across the target area creating a tomographic baseline in two directions.

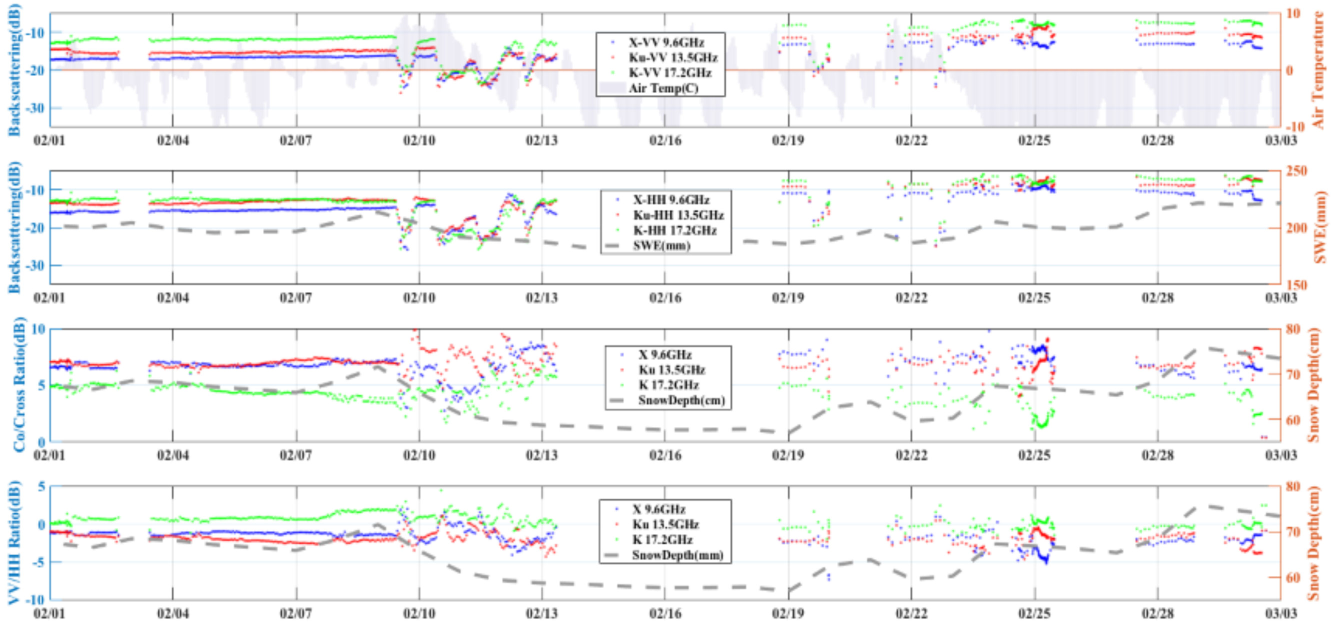


Fig. 3. Example of a figure caption. (*figure caption*)

Dual-antenna architecture was implemented to improve the isolation between the transmitter and receiver. This technique offers a 50 dB improvement in signal-to-noise ratio versus conventional single-antenna FMCW radar systems. With current setting, we could have around 30cm vertical resolution. This system provides an in situ research platform for developing and evaluating the accuracy of various tomographic methods for volumetric retrievals of SWE from snowpack at Earth Exploration-Satellite frequencies. The radar system is designed to run autonomously, providing a continuous dataset throughout the entire winter seasons, permitting snowpack retrievals at these radar frequencies to be analyzed for both short and long timescales. A commercial off-the-shelf LIDAR mounted to the side of the transceiver box complements the radar data by providing real time high-precision measurements of the snow surface layer height and topography.

The radar calibration has been done by measuring the radar cross section of a trihedral corner reflector from different distance. In figure 1, we plot the calibrated backscattering for each frequency and polarization verse the air temperature, snow depth, snow water equivalence and snow density. In early February, there were a few warm days and the backscattering drops as the snow become wet.

## III. Deployment at Fraser, CO

The system was deployed on a ground based tower at the Fraser Experimental Forest (FEF) Headquarters, near Fraser, CO, USA (39.847°N, 105.912°W) from February 1 to April 30, 2017 and run continuously with some gaps for required hardware supports. In situ measurements of snow depth and other snowpack properties were performed every week for comparison with the remotely sensed data. A network of soil moisture sensors, time-lapse cameras, acoustic depth sensors, laser depth sensor and meteorological instruments was installed next to the site to collect in situ measurements of snow, weather, and soil conditions.

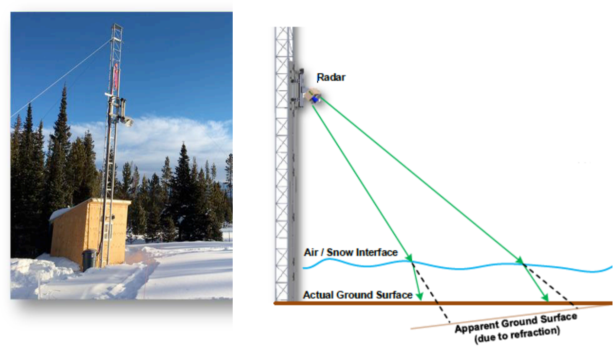


Fig. 1. Example of a figure caption. (*figure caption*)

## IV. Signal Processing and Tomography Results

The SRT3 processing chain consists of a standard FMCW FFT-based range compressor followed by a multi-looking time-domain back-projection processor. After anti-aliasing, downsampling, and leakage subtraction, the raw FMCW samples are range-compressed via an FFT with an appropriate apodization window. The data is zero-padded to produce an oversampled, sinc-interpolated range compression, which reduces the difficulty of later interpolation steps. Auxiliary information is used to split up the data into sets of 2D scans of 0.6 x 0.6 m. Since vertical cuts through the snow are targeted, each 2D scan is split up into vertical strips, on which a brute-force parallelized implementation of a back-projection algorithm is applied (similar to the phase-migration algorithms of ground penetrating radar). The resulting images are incoherently averaged in azimuth as power and coherence, producing a multi-looked cut of the snow profile. Although the multi-looking comes at the cost of azimuth resolution, it is critical for reducing the significant speckle and allowing the layers of snow to be identified. The implemented back-projection algorithm also makes use of the measured antenna

Fig. 2. Example of a figure caption. (*figure caption*)

pattern directivity (magnitude only, not phase) and of the radar equation to remove their impact on the power image.

Leakage and clutter dominate over thermal noise, as is common in FMCW radarPulse-to-pulse doppler shows non-random behavior and the range-compressed return has a coherence greater than 0.3out to at least 40~m, significantly beyond the region of interest. While there is little to be done about clutter, at least some degree of leakage can be compensated for by subtracting out a sky measurement. This brings the leakage down to the level of the returns of interest, which has a clear impact on the tomograms from the 2015/2016 campaign, where the leakage tended to focus onto boresight.

1. Snow Stratigraphy

The SRT3 processing chain consists of a standard FMCW FFT-based range compressor followed by a multi-looking time-domain back-projection processor. In Figure 3, we show a focus tomograms of 12 look averaging on Feb 1, 2017. The red line is ground reference position derived from the snow-free laser measurement. The plot demonstrates the coherency of the vertical slice. As the frequencies increases, the volume scattering from the snow become more prominent. The snow density of the pit measurement also matches coherency distribution.

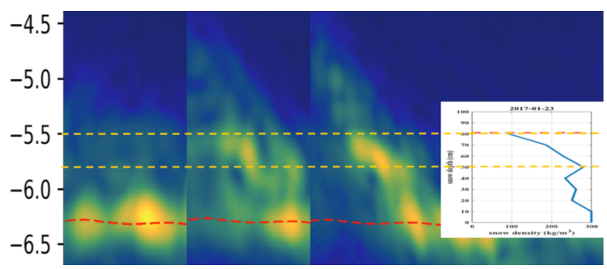


Fig. 1. Example of a figure caption. (*figure caption*)

2 . Diurnal Thawing and Refreezing Cycle

In February, there are a few warmer days. The snow went through thawing and refreezing process during a day. The tomograms shows that when the snow is wet, the higher coherency shifted from snow-ground interface to air-snow interface due to the high permittivity contrast between wet snow and air.

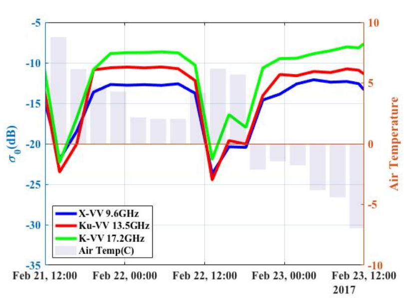


Fig. 2. Example of a figure caption. (*figure caption*)

3. Snow Density Retrieval

There is a horizontal shift of features in snow volume due to refraction in Figure 4. The snow density can by computed by realigning the top plot to bottom. The figure 7 shows the refraction phenomena.

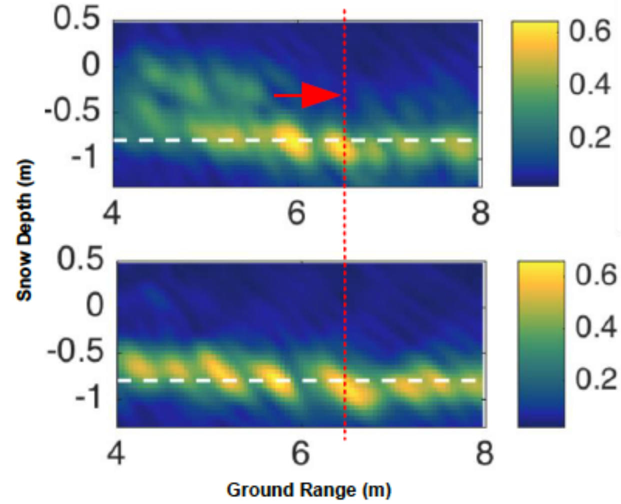


Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity “Magnetization”, or “Magnetization, M”, not just “M”. If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write “Magnetization (A/m)” or “Magnetization {A[m(1)]}”, not just “A/m”. Do not label axes with a ratio of quantities and units. For example, write “Temperature (K)”, not “Temperature/K”.

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## Reference


[1] Sturm, M., Goldstein, M. A., & Parr, C. (2017). Water and life from snow: A trillion dollar science question. *Water Resources Research*.

[2] Shi, J., Xiong, C., & Jiang, L. (2016). Review of snow water equivalent microwave remote sensing. *Science China Earth Sciences*, *59*(4), 731-745.

[3] Marshall, H.-P., M. Schneebeli, and G. Koh (2007), "Snow stratigraphy measurements with high-frequency FMCW radar: comparison with snow micro-penetrometer," Cold Regions Science and Technology, vol. 47, pp. 108-117.

[4] Ferro-Famil, L., Huang, Y., & Pottier, E. (2015). Principles and applications of polarimetric SAR tomography for the characterization of complex environments. In VIII Hotine-Marussi Symposium on Mathematical Geodesy (pp. 243-255).

[5] Ferro-Famil, L., Tebaldini, S., Davy, M., & Boute, F. (2014, June). 3D SAR imaging of the snowpack at X-and Ku-Band: results from the AlpSAR campaign. In *EUSAR 2014; 10th European Conference on Synthetic Aperture Radar; Proceedings of* (pp. 1-4). VDE

[6] Frey, O., Werner, C. L., & Wiesmann, A. (2015, September). Tomographic profiling of the structure of a snow pack at X-/Ku-Band using SnowScat in SAR mode. In *Radar Conference (EuRAD), 2015 European* (pp. 21-24). IEEE.

[7] Morrison, K., & Bennett, J. (2014). Tomographic profiling—A technique for multi-incidence-angle retrieval of the vertical SAR backscattering profiles of biogeophysical targets. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(2), 1350-1355.

[8] Rekioua, B., Davy, M., Ferro-Famil, L., & Tebaldini, S. (2017). Snowpack permittivity profile retrieval from tomographic SAR data. *Comptes Rendus Physique*, *18*(1), 57-65.